The First Years - Experience of LHC Beam Instrumentation

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Rhodri Jones

(CERN Beam Instrumentation Group)

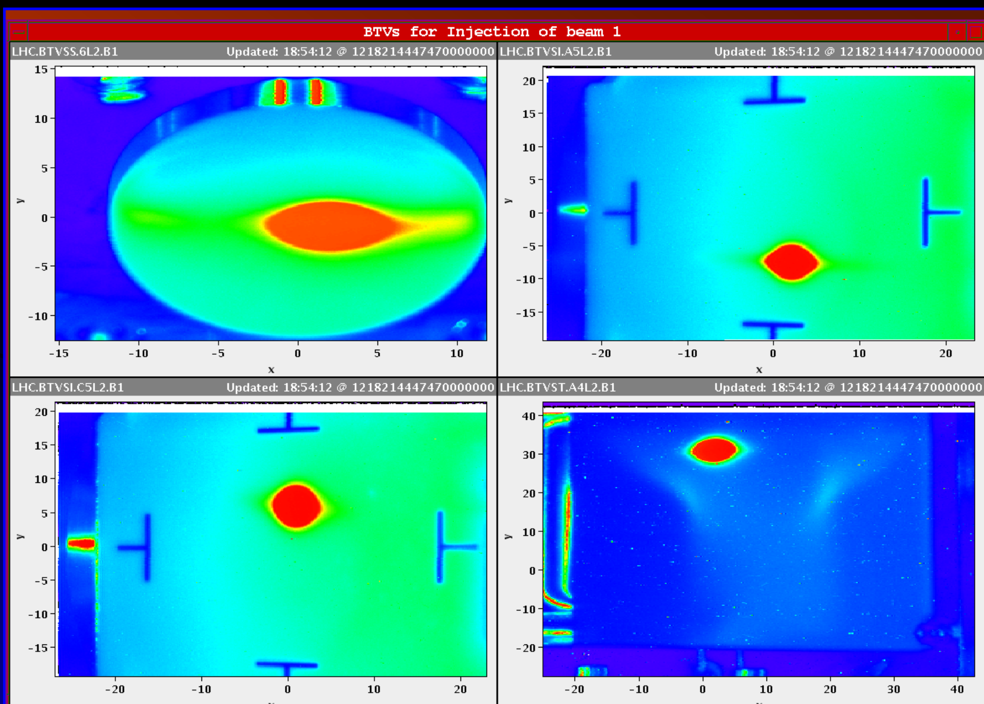
Outline

The use of Beam Instrumentation in Commissioning and Understanding the LHC

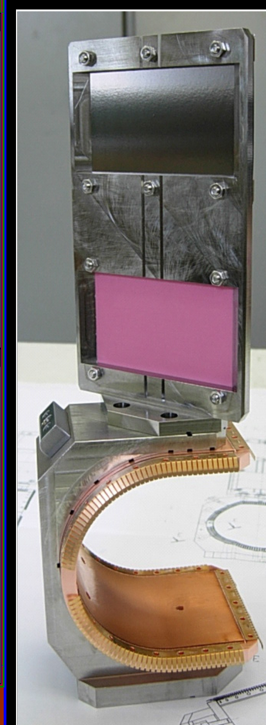
- Early Diagnostics
- Safe Operation
  - Machine Protection
- Optimisation of Operation
  - Beam Based Feedbacks
  - Synchrotron Light Diagnostics
- Helping the Experiments
  - Luminosity calibration
- Future Developments

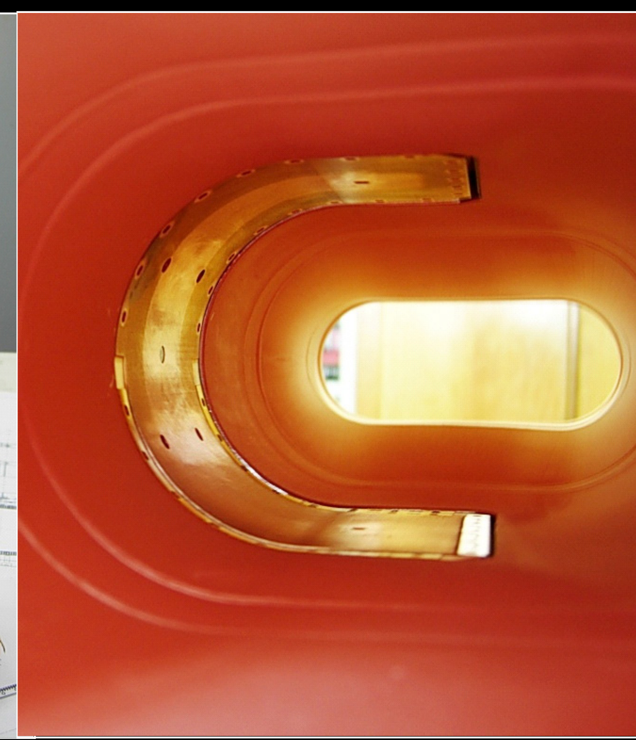
Early Diagnostics

- Threading the first pilot bunch round the LHC ring
  - Injection – visible on scintillator screens
  - Trajectory – using BPMs one beam at a time, one hour per beam
  - Closed orbit – BPMs updating at 1Hz
  - Dump lines – visible on BPMs and large scintillator screen



First Beam in the LHC 8/8/2008





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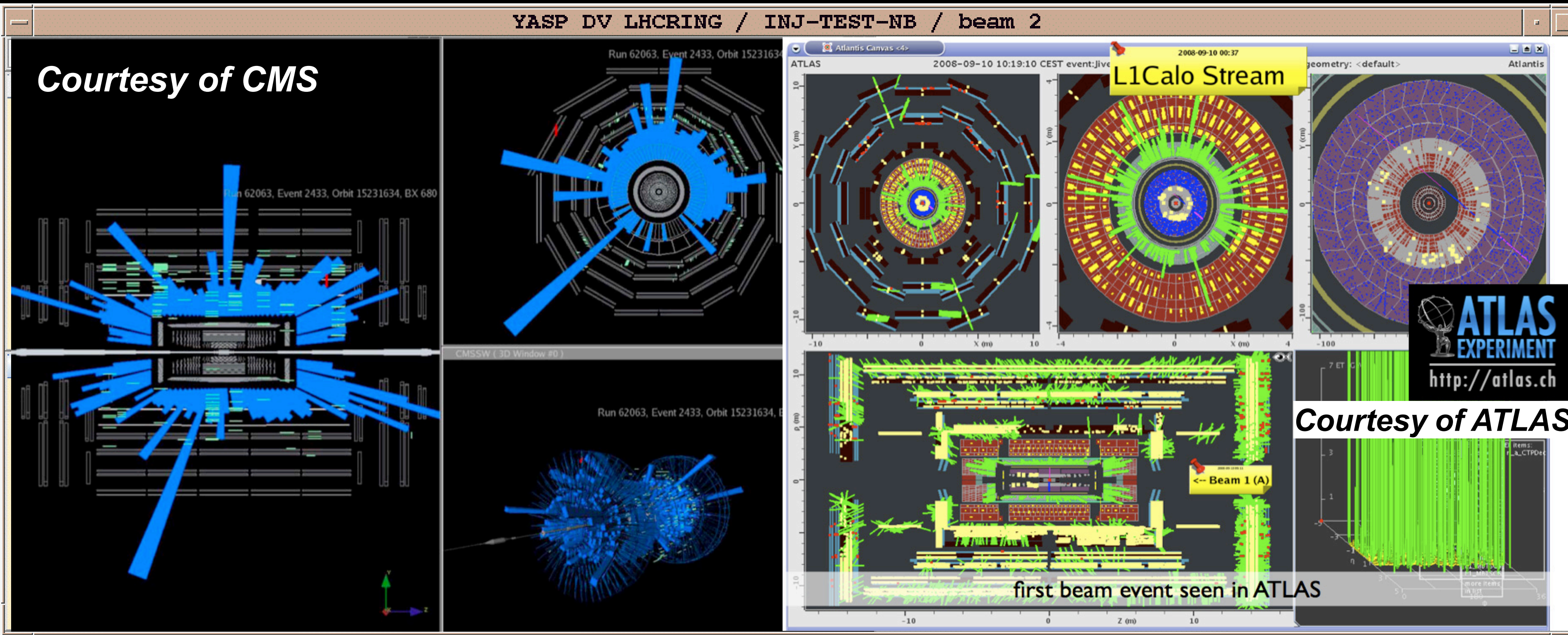
BPM availability ~ 99%



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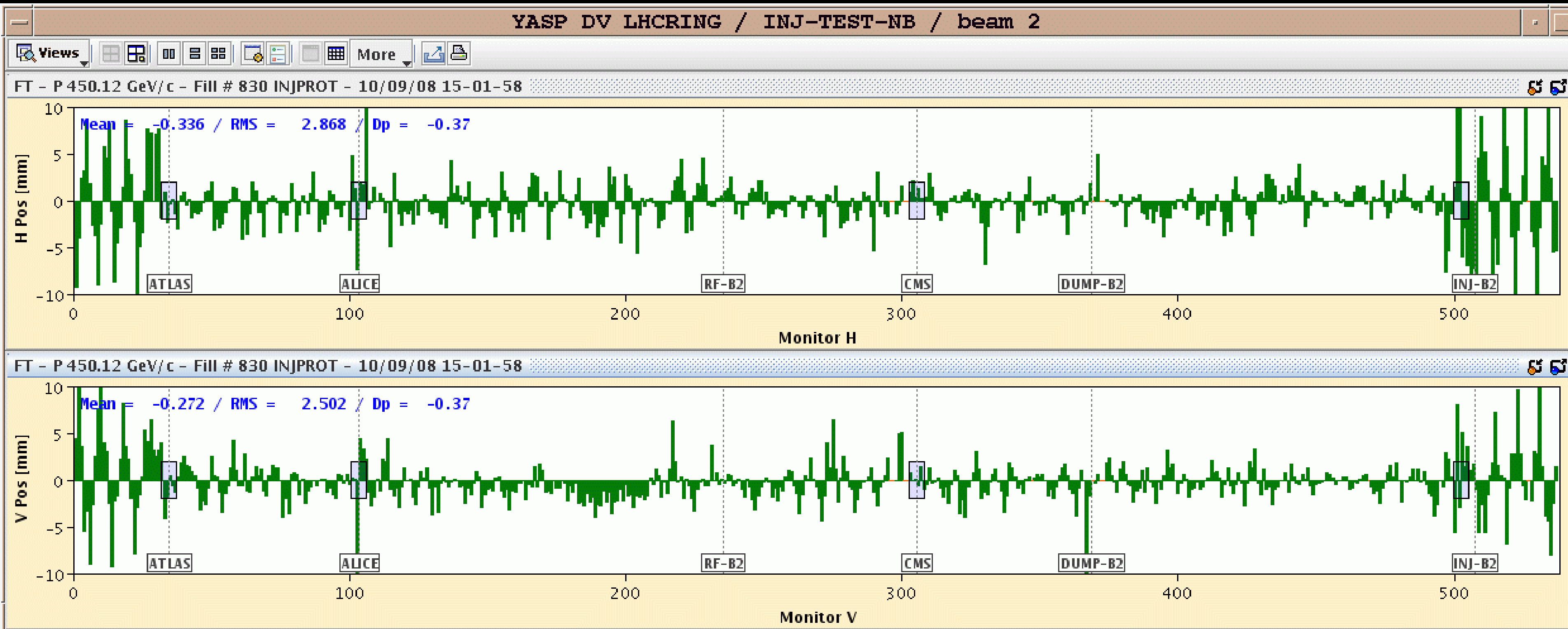

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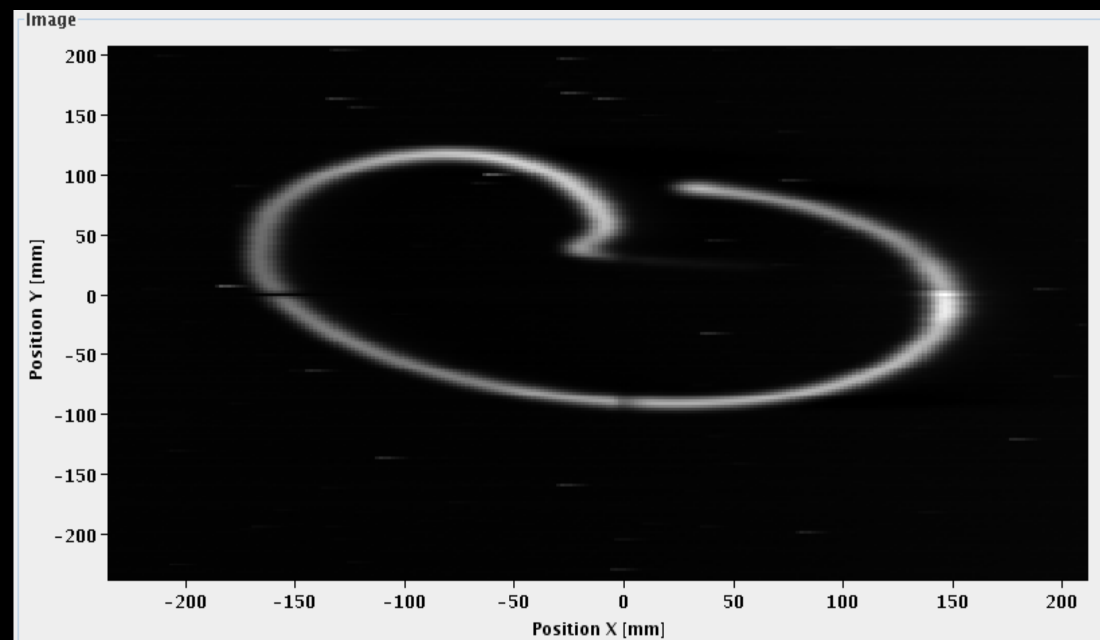


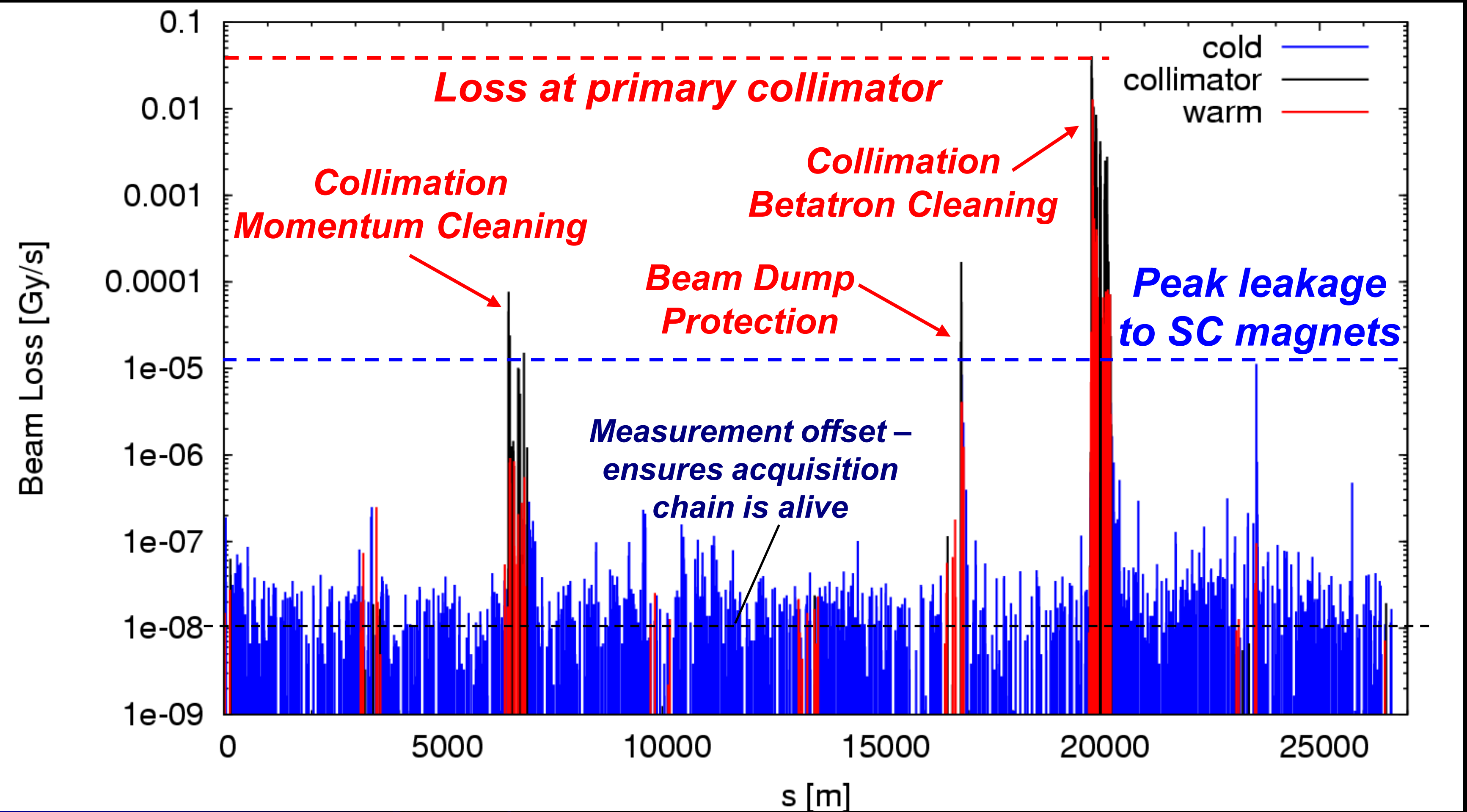
Uncaptured beam sweeps through the dump line

Safe Operation - Machine Protection

- Role of the BLM system:
  - Protect the LHC from damage
  - Dump the beam to avoid magnet quenches
  - Diagnostic tool to improve the performance
- Design criteria
  - Signal speed and reliability
  - Dynamic range > 10^9
    - Electronics ⇒ 10^7
    - Choice of detector ⇒ 10^4
- Detectors
  - ~3600 Ionisation Chambers (IC)
    - 50 cm, 1.5l N_2 gas filled at 1.1 bar
    - Ion collection time 85 μs
  - ~300 Secondary Emission Monitors (SEM)
    - 10 cm, pressure < 10^{-7} bar
    - ~ 30000 times smaller gain than IC
- Electronics
  - Current to Frequency conversion
  - Losses integrated & compared to threshold table
    - 12 time intervals (1 turn to 100s) and 32 energy ranges

BLMs & Collimation

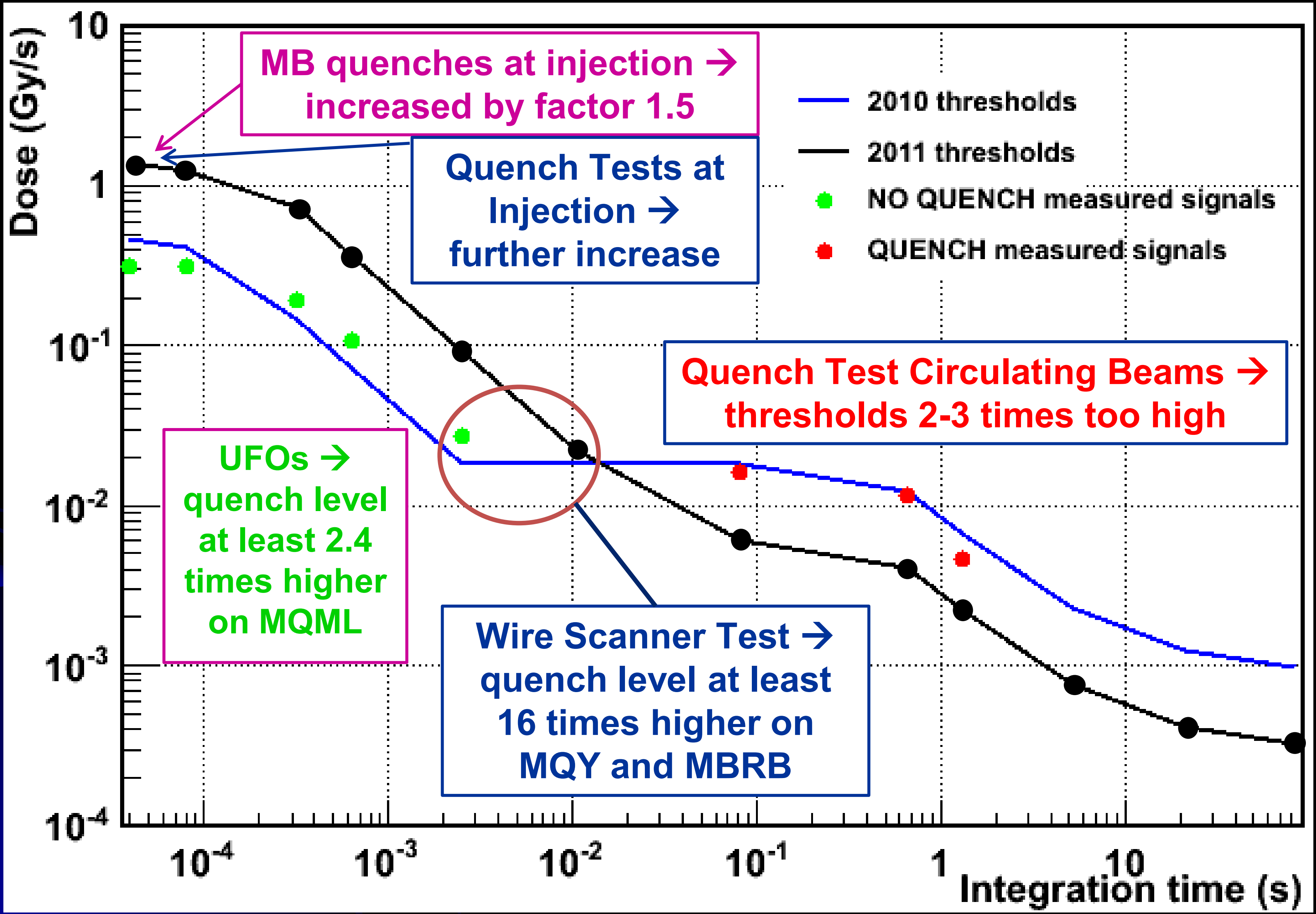
- Full collimation setup
  - BLM system used both for setting-up and qualifying
  - Beam cleaning efficiencies ≥ 99.98% ~ as designed



Observing Fast Losses

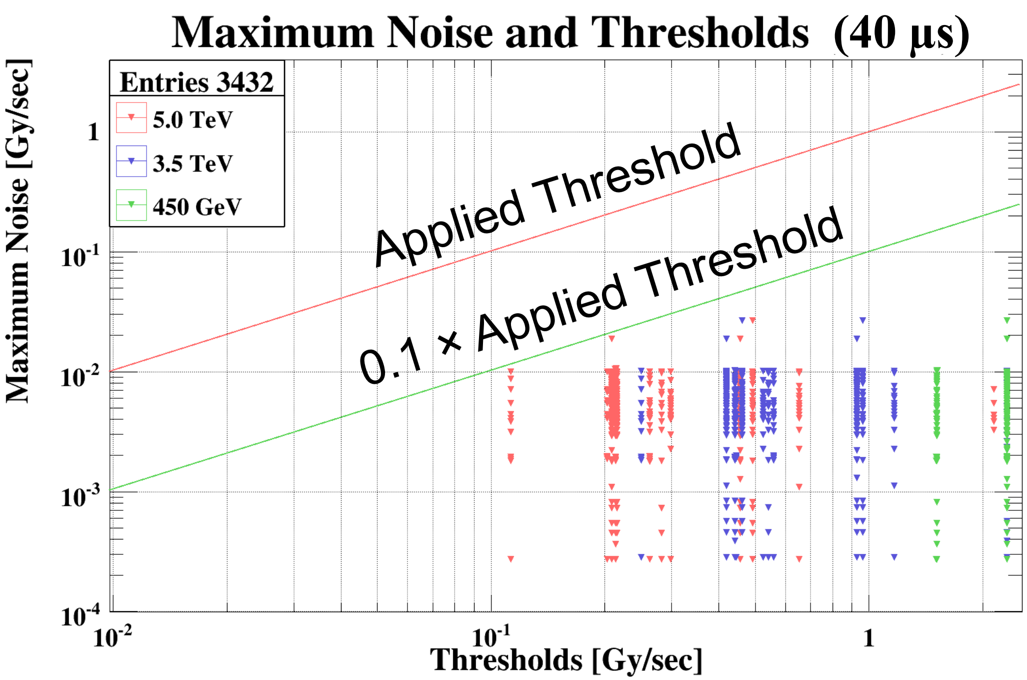
- 7th July 2010 – BLMs request beam dump as result of fast (ms) beam loss
  - Since then 35 beam dumps requested due to similar losses
  - Believed to be caused by “Unidentified Falling Objects” or UFOs
  - Subsequent study showed more than 5000 candidates - most well below threshold
  - UFO rate during physics fills is now ~5 per hour

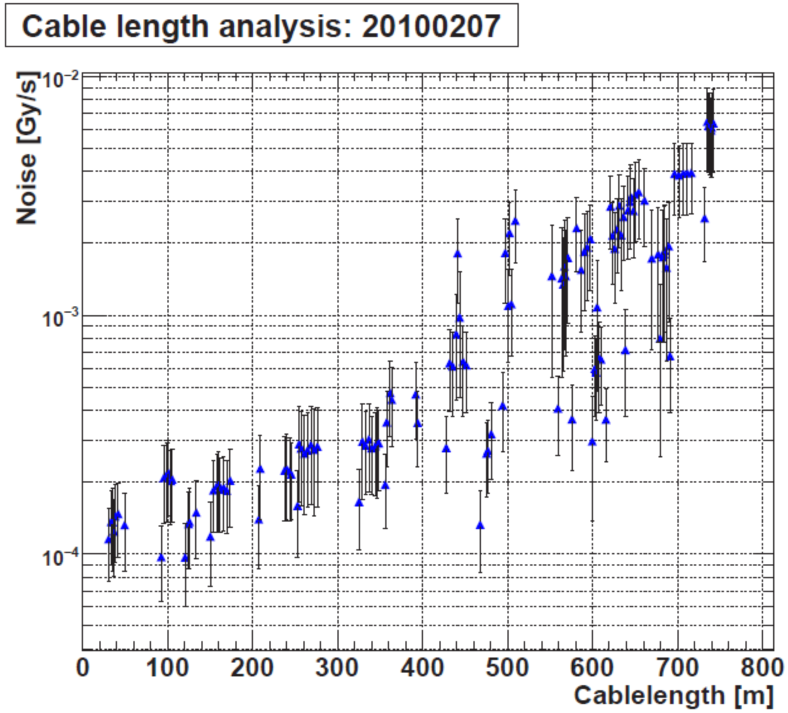
BLM Thresholds



Thresholds Compared to Noise Levels

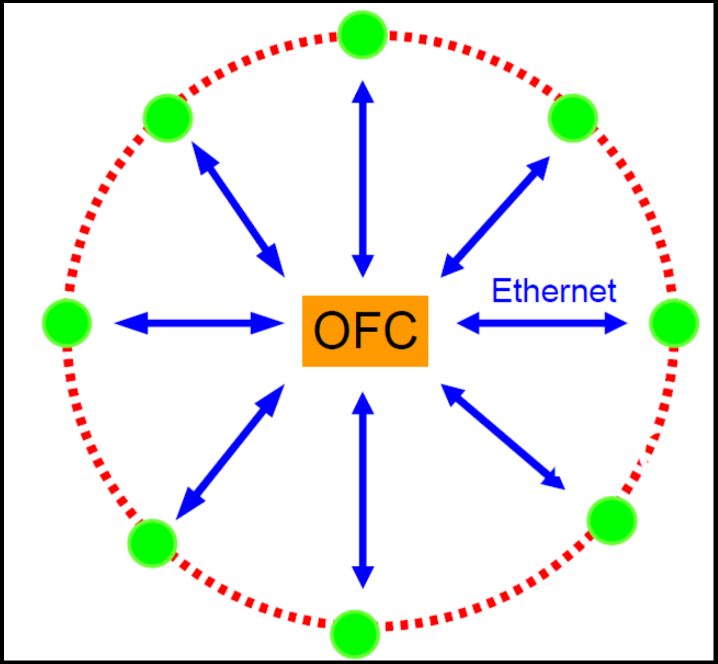
- Are the thresholds safely above the noise levels?
  - YES up to 5TeV
  - Noise proportional to cable length
  - May require RadHard ASIC CFC for full performance at 7TeV
    - Would allow mounting front-end electronics near BLM





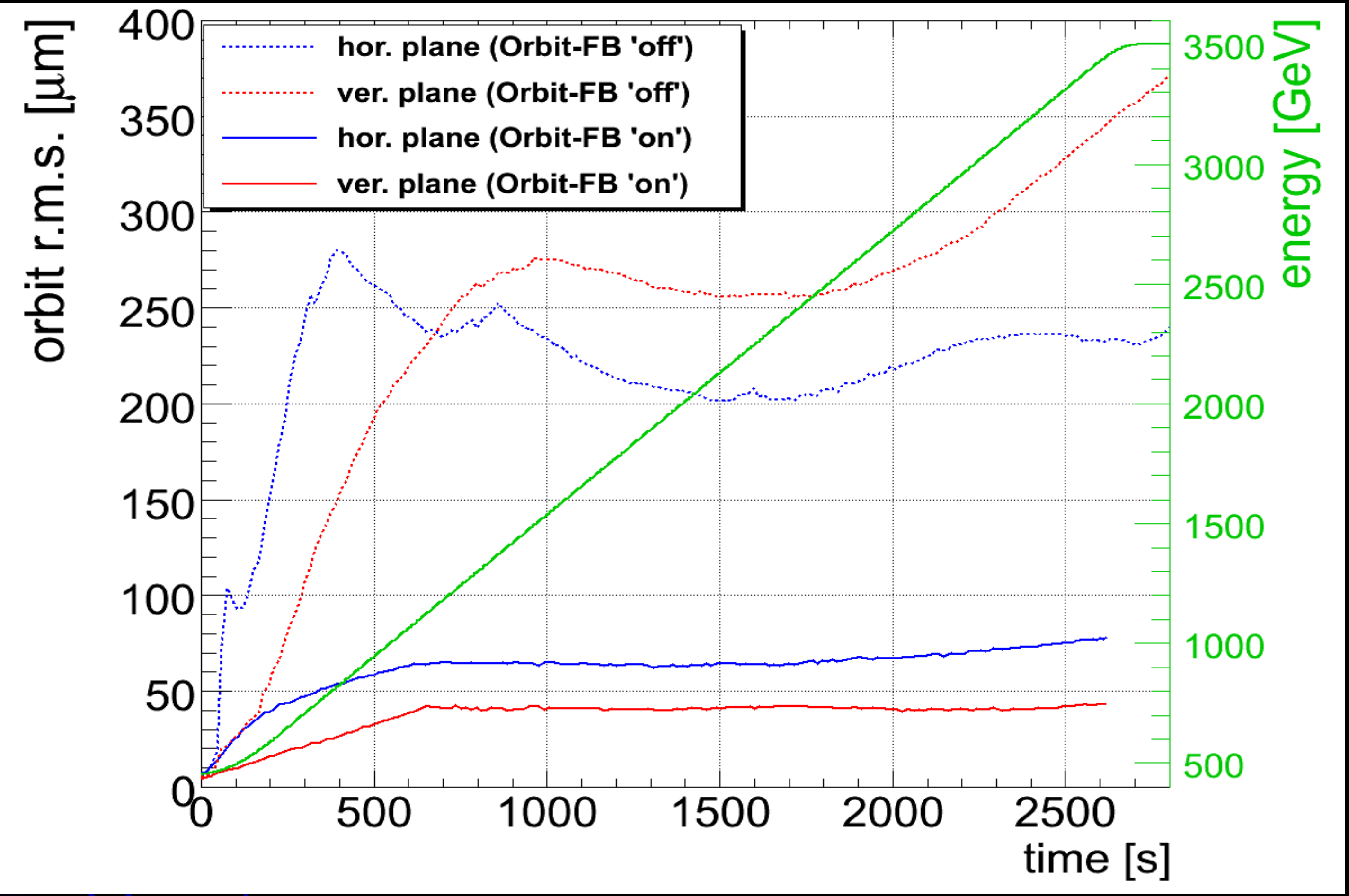
Machine Optimisation - Feedbacks

- Opted for central global feedback system regrouping:
  - Orbit, energy, tune (operational)
  - Chromaticity, coupling (tested)
- Initial requirements:
  - Chromaticity expected to be most critical parameter for real-time control
    - Large perturbations foreseen & tight tolerances required
  - BUT
    - Large losses during early ramps changed focus to tune followed by orbit feedback



- Orbit-Feedback is the largest and most complex LHC feedback:
  - 1088 BPMs → 2176+ readings @ 25 Hz from 68 front-ends
  - 530 correction dipole magnets/plane, distributed over ~50 front-ends
- Total >3500 devices involved
  - more than half the LHC is controlled by beam based feedbacks!

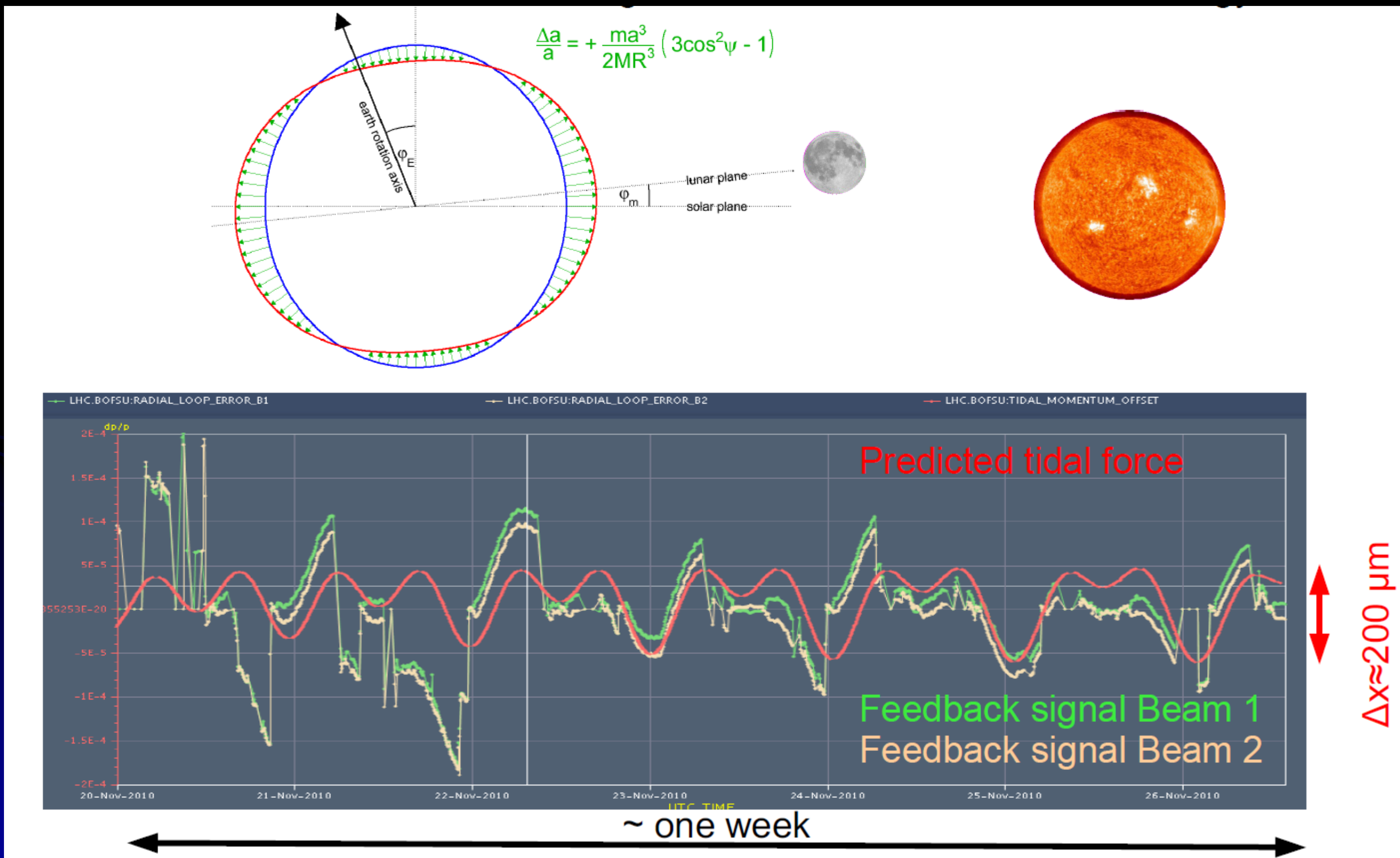
Orbit Feedback in the LHC



- Bandwidth of 0.1 Hz with BPM data supplied at 25Hz
- Regularised SVD approach to calculate applied correction
- Can maintain orbit stability to better than ~70µm globally & ~20µm in the arcs

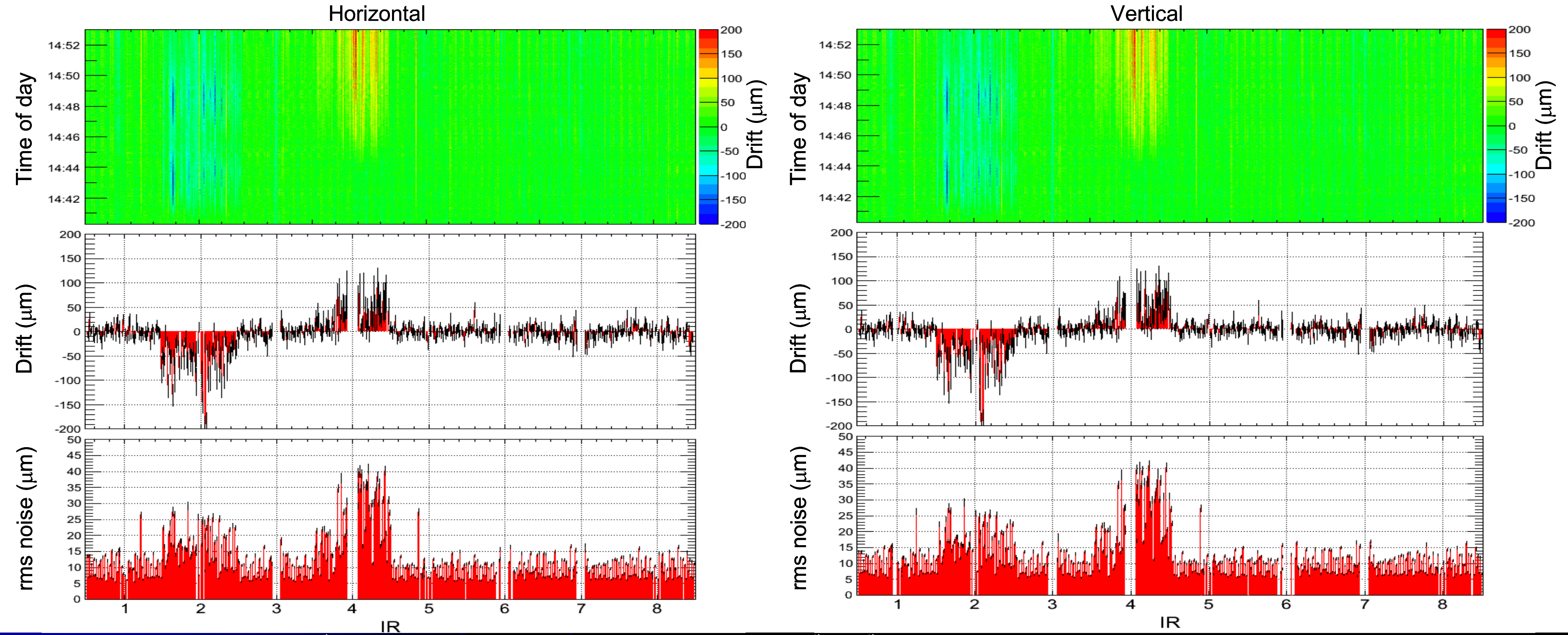
Orbit Feedback in the LHC

- Earth Tides dominating Orbit Stability during Physics

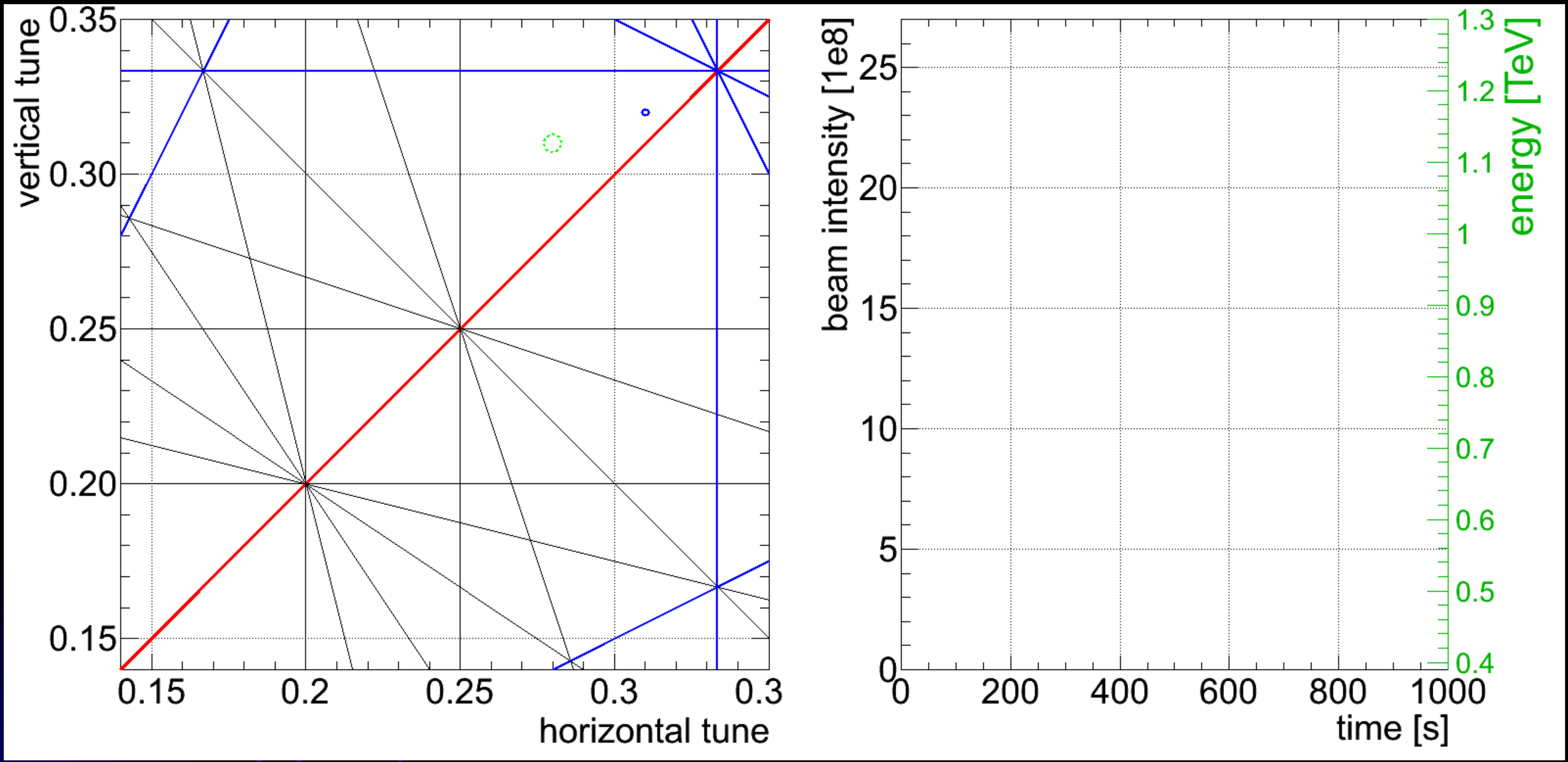


Orbit Stability Limitations

- Main performance limitation of orbit feedback
  - Systematic BPM reading dependence on temperature
    - Initially caused drifts up to 300μm on long-term orbit
    - Suppressed to the order of 100μm by
      - Calibration before each fill
      - Temperature compensation of each individual BPM channel
    - Long term solution - place electronics in temperature controlled racks

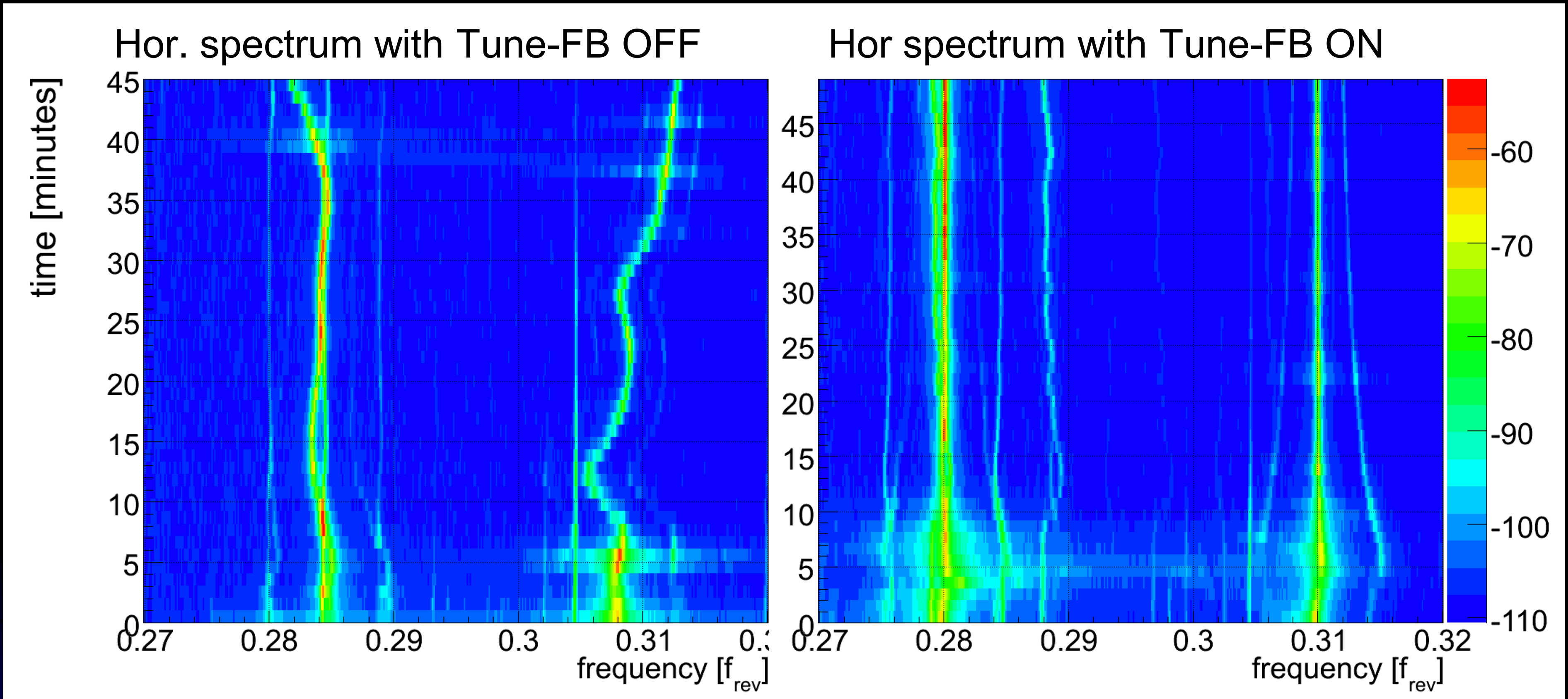


The LHC Tune System



- Base Band Tune (BBQ) Measurement System
  - Direct diode detection, heavy filtering & baseband acquisition using audio ADCs
  - Shows extremely high sensitivity
  - Most measurements possible with residual beam oscillations
    - No need for PLL system with tune determination using FFT peak fitting

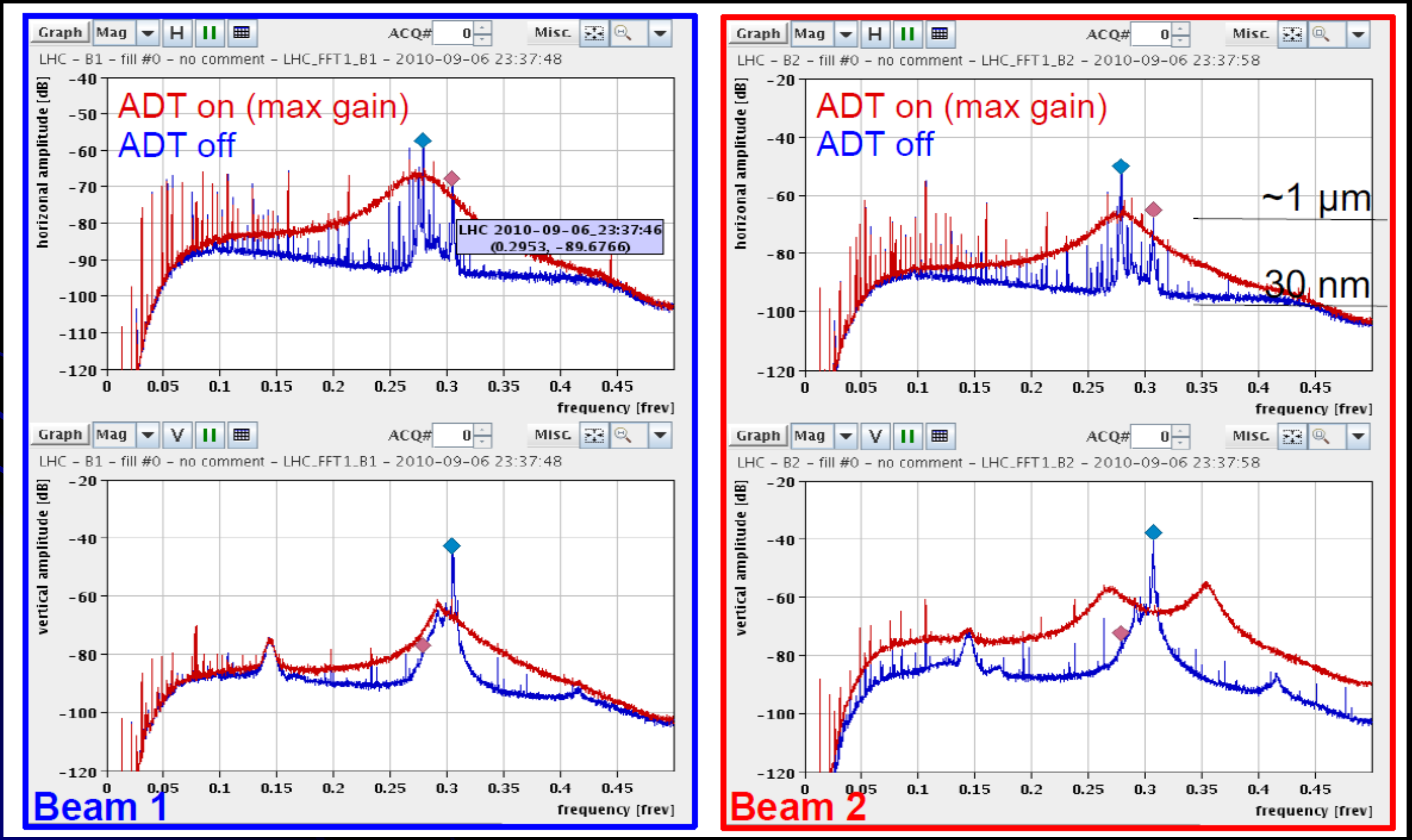
Tune Feedback in the LHC



- With full pre-cycling the fill-to-fill stability is now typically 2-3×10^{-3}
- Variations frequently increase up to 0.02
  - Due to partial or different magnet pre-cycles after e.g. access or sector trips
- Tune-FB routinely used for physics ramps to compensate these effects
  - Using peak fit on FFT with 0.1..0.3 Hz Bandwidth

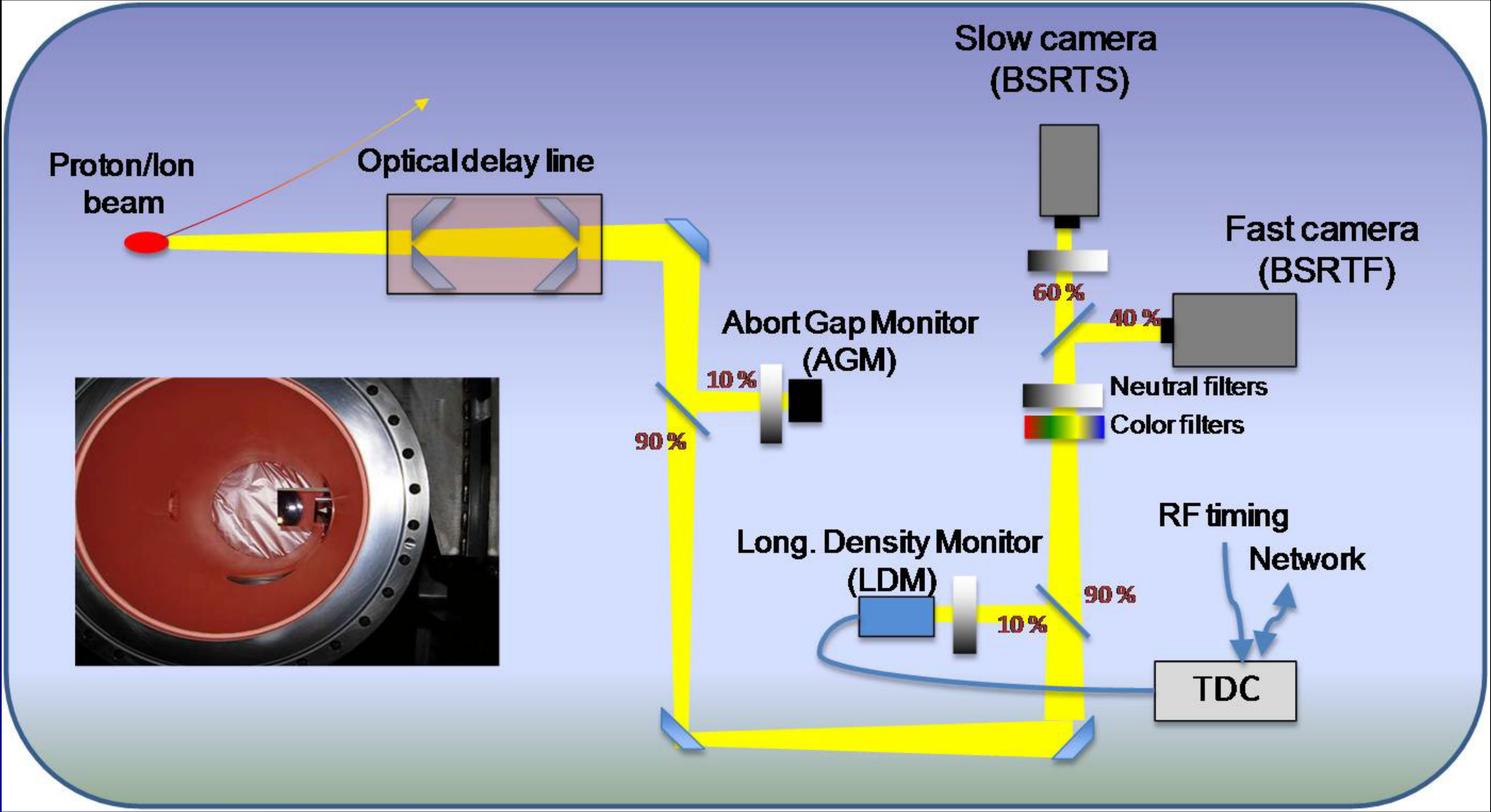
Tune Feedback & Active Damping

- BBQ noise-floor raised by 30 dB
  - wide tune peak → reduces tune resolution from 10^{-4} → $\sim 10^{-2}$
  - Impacts reliable tune (and coupling) measurement & feedback
  - Incompatible with chromaticity measurements using small Δp/p-modulation
- Only solution found so far is to run damper with lower gain



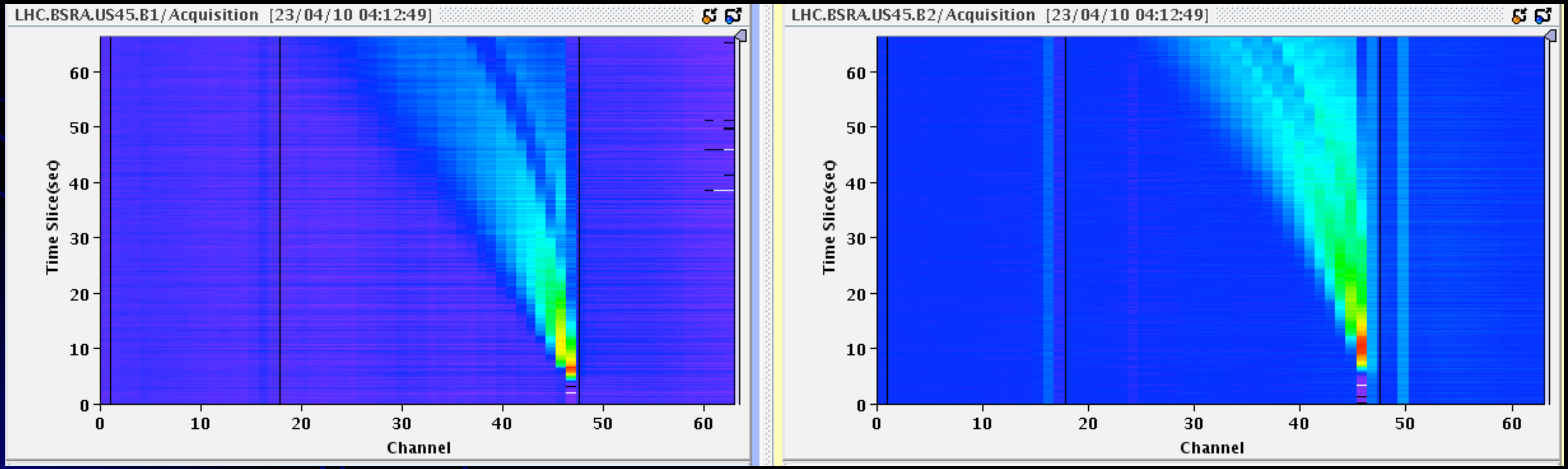
Optimisation of Operation

- Synchrotron Light Diagnostics
  - Energy high enough to obtain sufficient visible light for protons & ions
    - SC undulator used below 1.2TeV until radiation from D3 dipole takes over



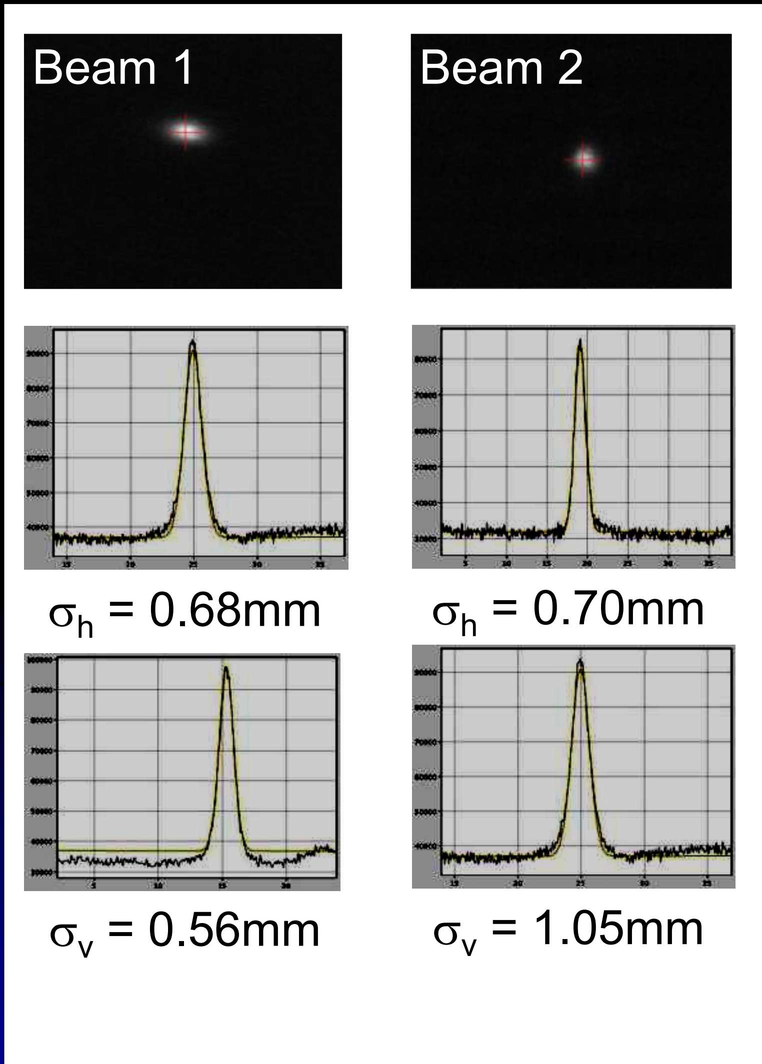
Optimisation of Operation

- Monitoring of the 3μs abort gap
  - Every 100ms detect if gap population over 10% of quench level
    - 10^5 protons in100ns at 7TeV but plenty of photons
    - Most challenging at 1.2TeV with low light levels (5×10^7 prot / 100ns)
  - Uses gated Multi Channel Plate / Photomultiplier
    - Gated photomultiplier gets ~15% of collected synchrotron light
    - Photomultiplier gated off except during the 3μs abort gap
  - Integration using LHCb integrator ASIC
    - Gap observed in 30 bins with 100ns resolution

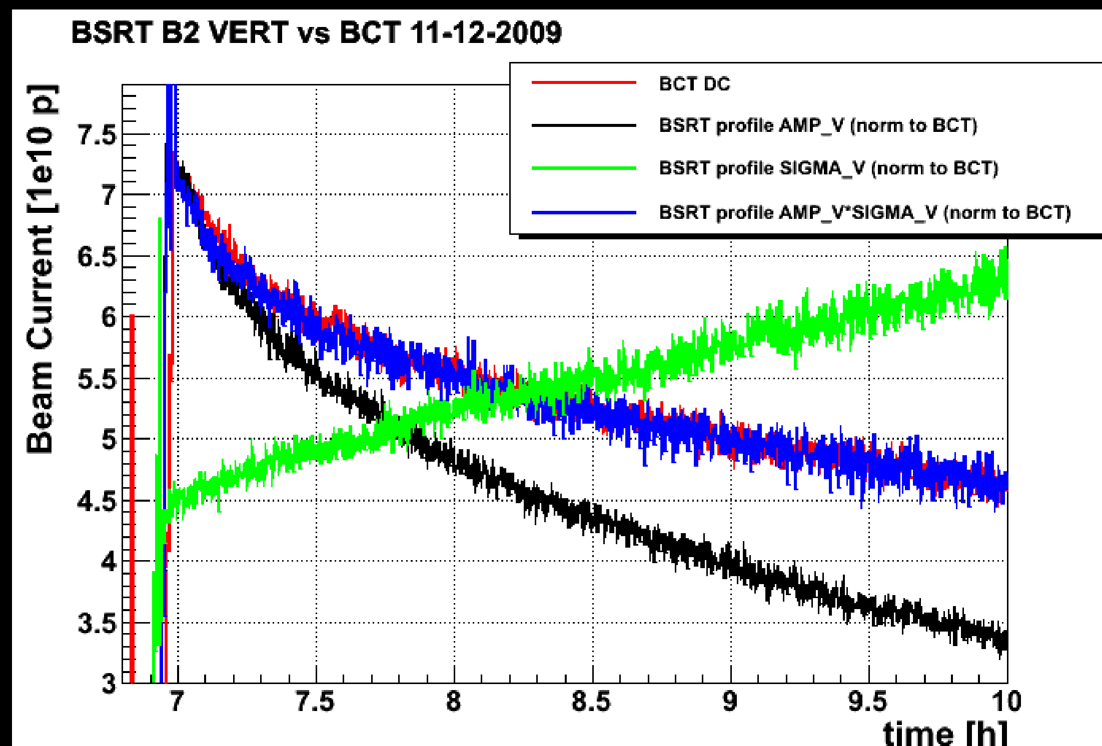


  - Single pilot debunching when the RF is switched OFF

Transverse Profile Measurement

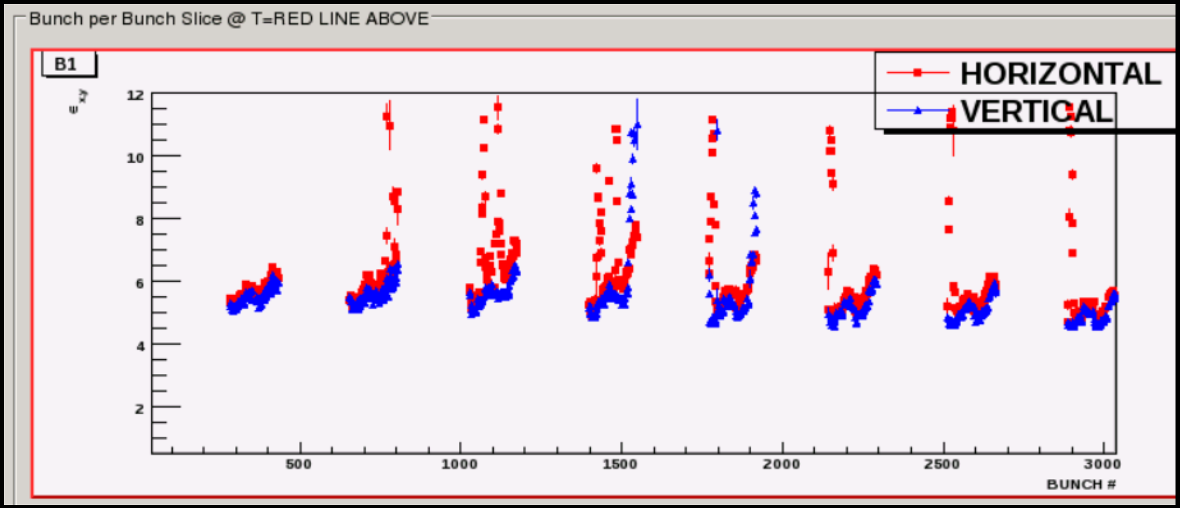


- CCD camera fitted with gated intensifier
  - Used from very early stage to investigate emittance growth
  - Understanding of the optics & error sources ongoing for absolute calibration

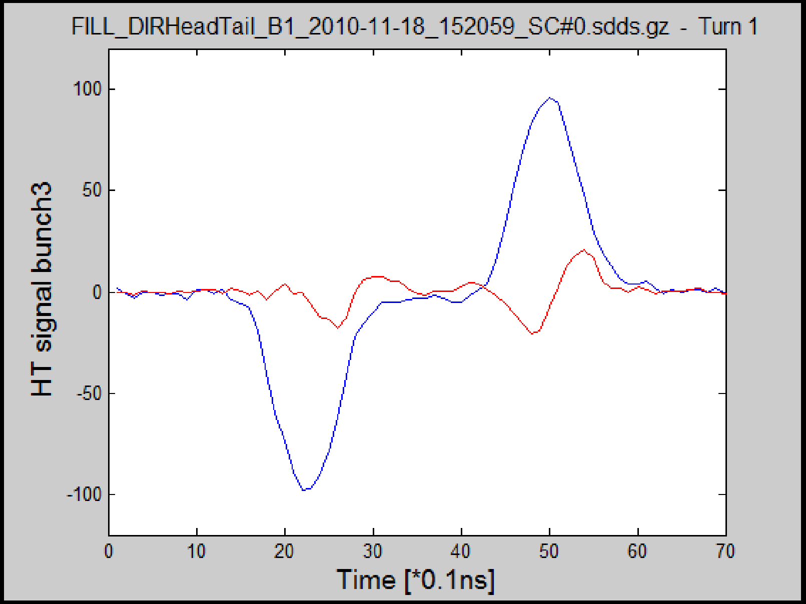


Bunch by Bunch Transverse Profiles

- In 2011 implemented gated mode
  - Allows profile of single bunch to be captured in a few seconds
- Operational uses
  - Identify instabilities leading to emittance growth
  - Verify correct injection parameters from injectors
- Limitations
  - Time required to scan over all bunches
    - 10 times faster readout being investigated
    - Intensified fast camera under test



804 bunches – with strong electron cloud activity



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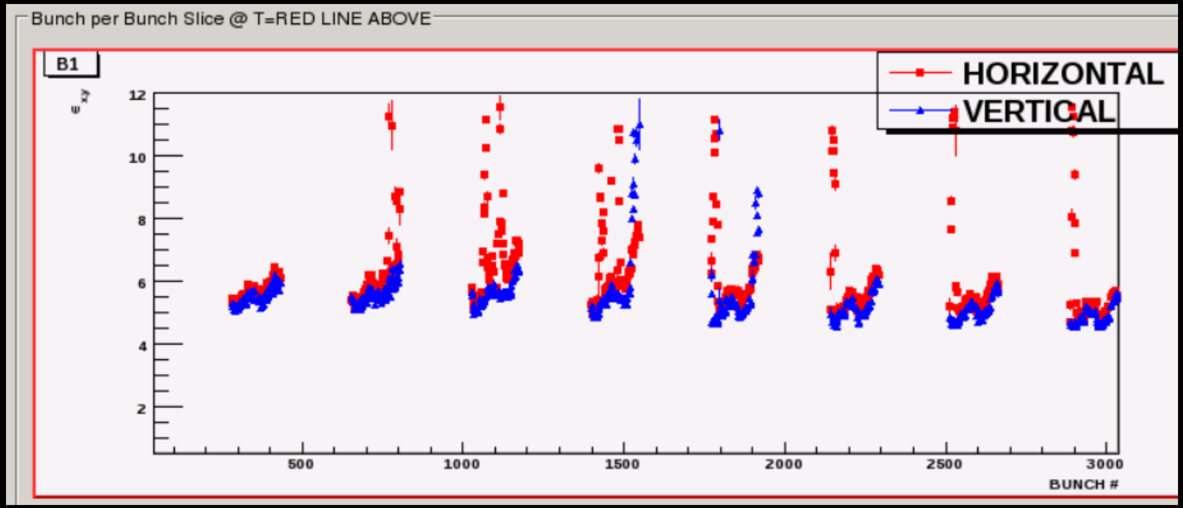

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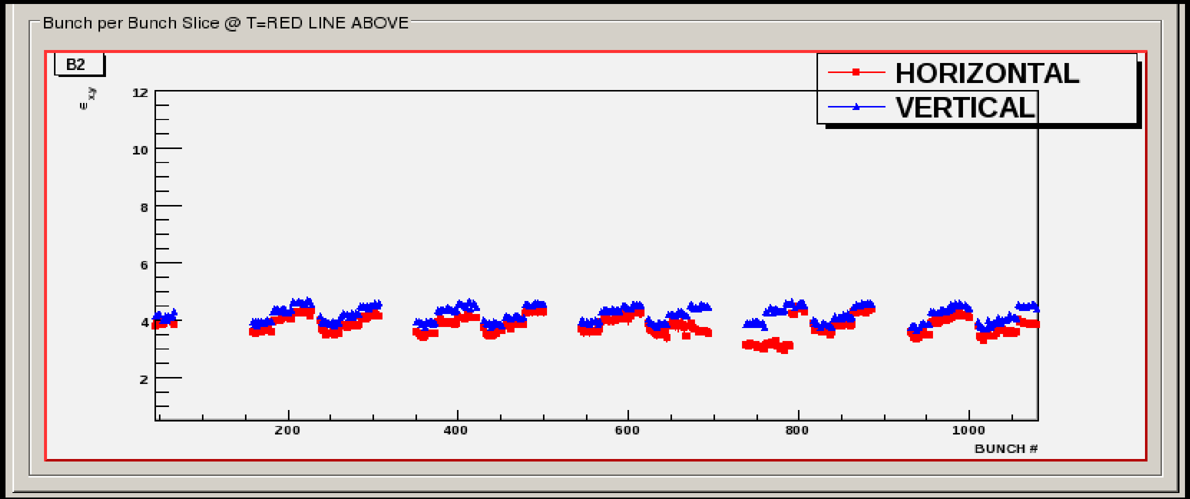
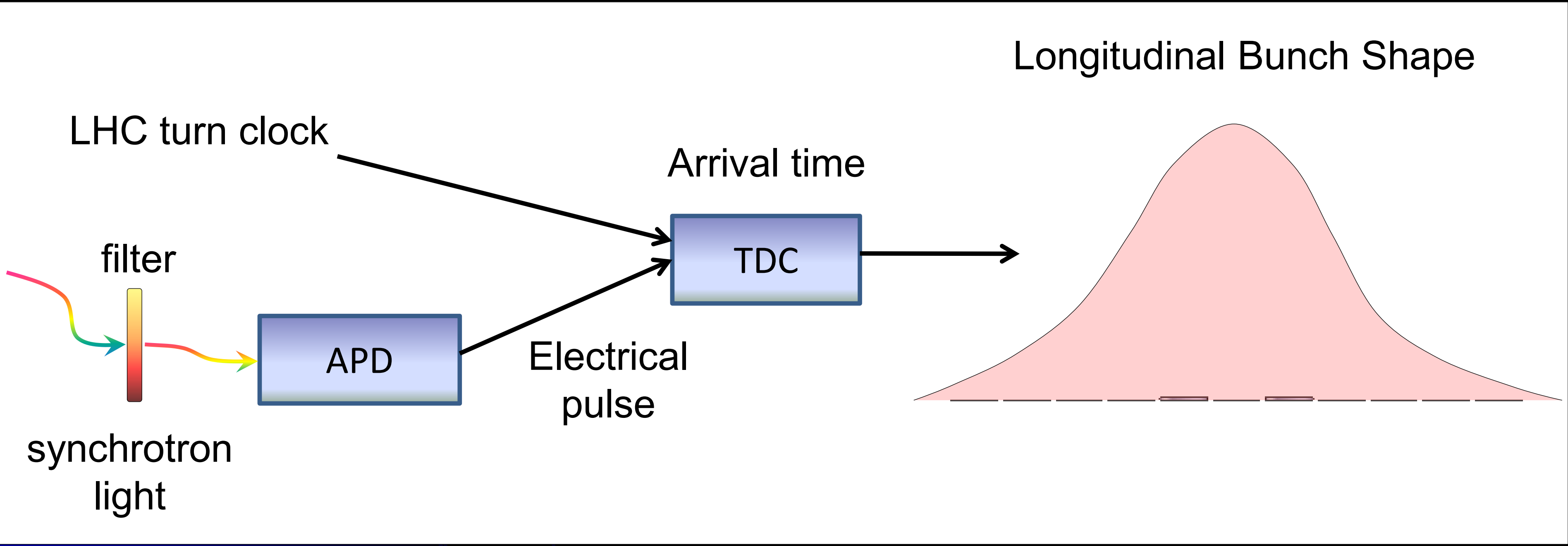


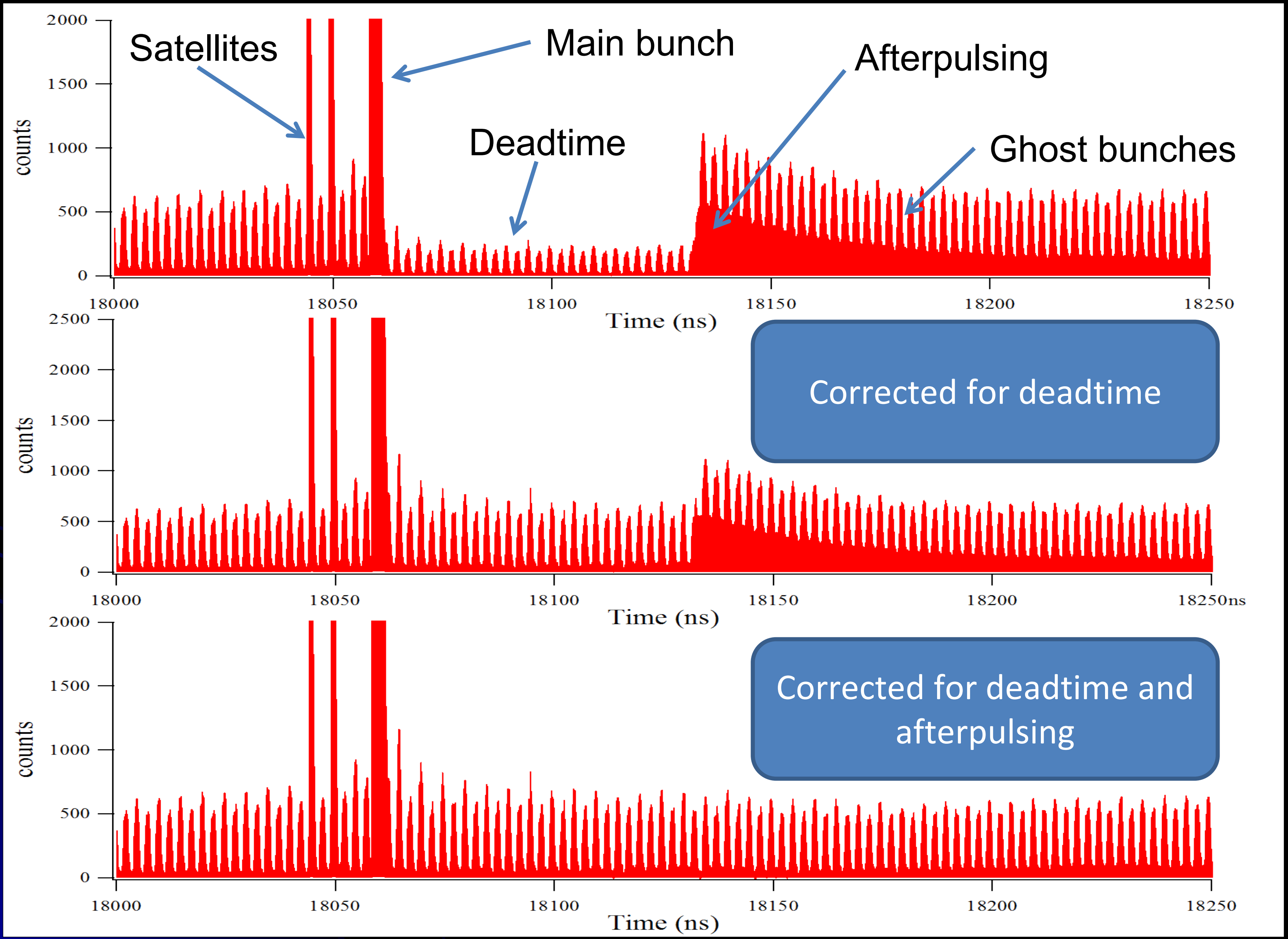
after some time of vacuum chamber scrubbing

Longitudinal Density Monitor (LDM)

- Aims:
  - Profile of the whole LHC ring with 50ps resolution
  - High dynamic range for ghost charge measurement
- Method:
  - Single photon counting with Synchrotron light
    - Avalanche photodiode detector
    - 50ps resolution TDC

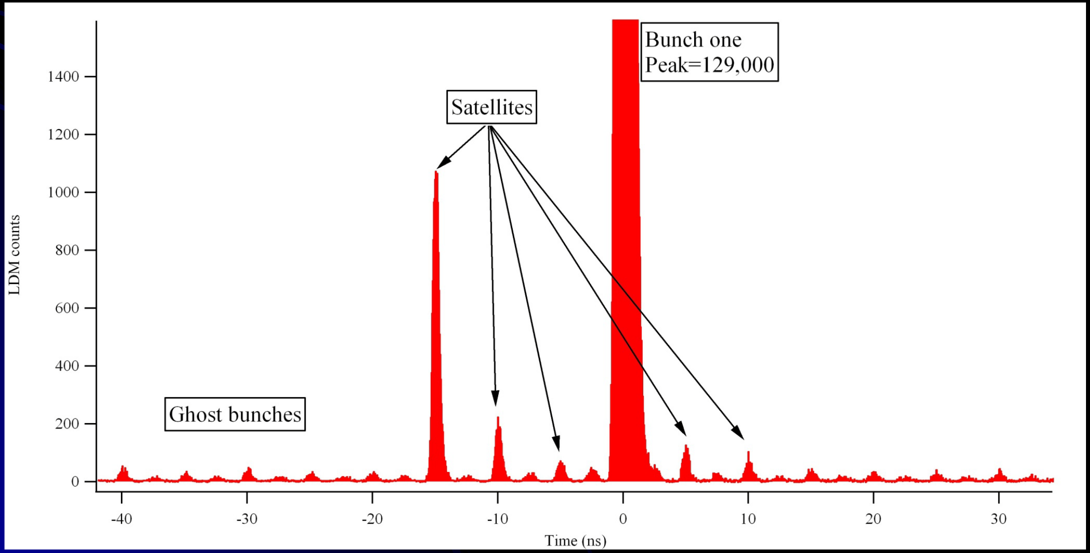


LDM On-line Correction



LHC Optimisation with the LDM

- Achievements:
  - Dynamic range of up to 10^5 with integration time of a few minutes
- Used for:
  - Injector optimisation
    - Detection of large satellite populations
      - Led to injection cleaning using transverse damper
      - Avoids triggering beam dump due to satellites kicker out by injection kicker
  - Optimisation of LHC RF
    - Ghost bunches observed during LHC ion run in 2010
    - Came from RF manipulations to improve capture efficiency of main bunches



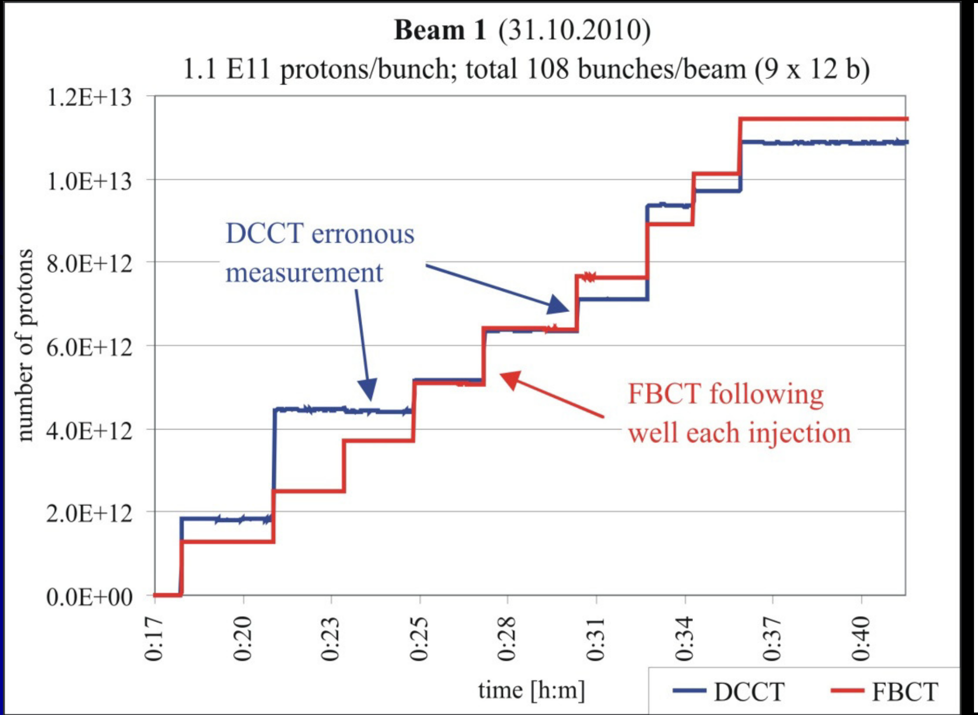
Lead ions at 3.5 Z TeV
10 min integration

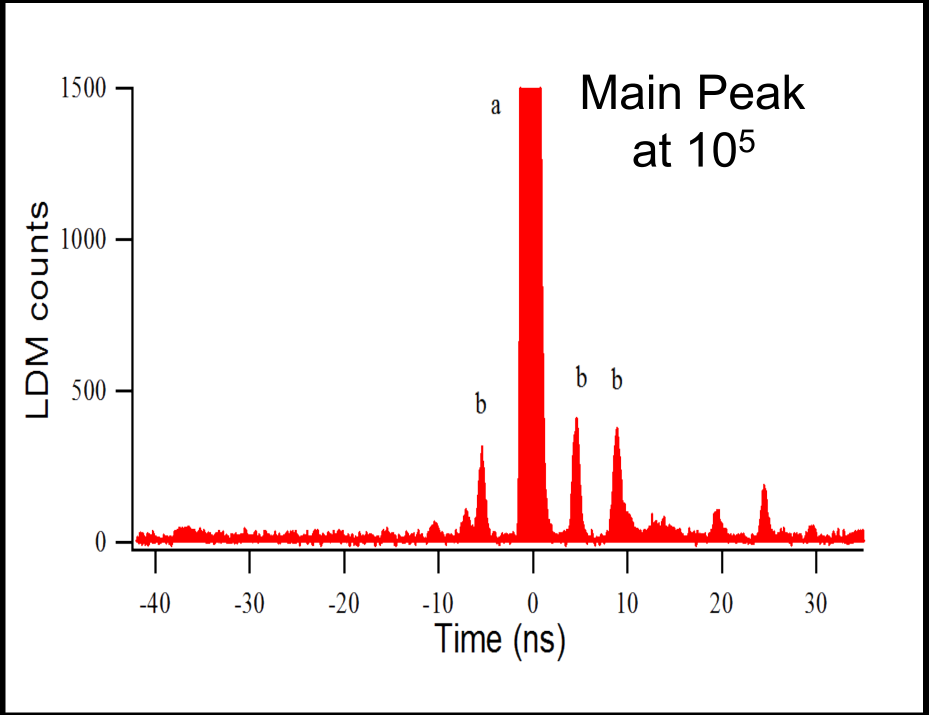
Helping the Experiments

- LHC Experiments use precise cross-section measurements to constrain *pp* interaction models & detect or quantify new phenomena due to physics beyond the Standard Model
  - Required accuracy on absolute value of cross section is 1-5%
- Two methods used in LHC
  - "van der Meer scan"
  - "beam-gas imaging"
- Both methods require a measurement of the individual populations of the bunches contributing to the luminosity
- Providing bunch by bunch intensity for absolute luminosity calibration is the job of the LHC Beam Current Transformers
  - Their errors was a major contribution to the final precision in 2010
    - estimated 3% absolute accuracy of bunch population measurement
  - Triggered fruitful collaboration between BI Group & LHC Experiments
    - Pushed LHC Beam Current Transformer performance to its limits
    - Well beyond requirements for normal operation

BCT Error Sources & their Mitigation

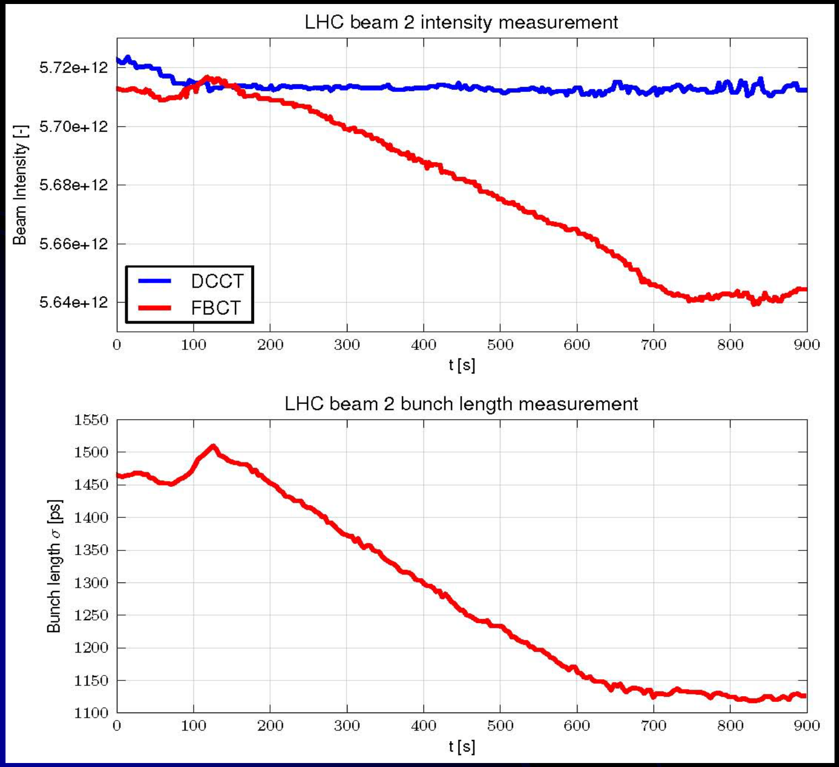
- Bunch pattern dependence & saturation of the DCCT
  - Modified DCCT feedback loop, wall-current bypass & front-end amplifiers
  - Uncertainty in the absolute DCCT calibration now at the 0.1% level
- Satellite bunches and unbunched beam
  - Produces uncertainty in cross-calibration of FBCT with DCCT
  - LDM & data from experiments used to ensure this is well below 1%

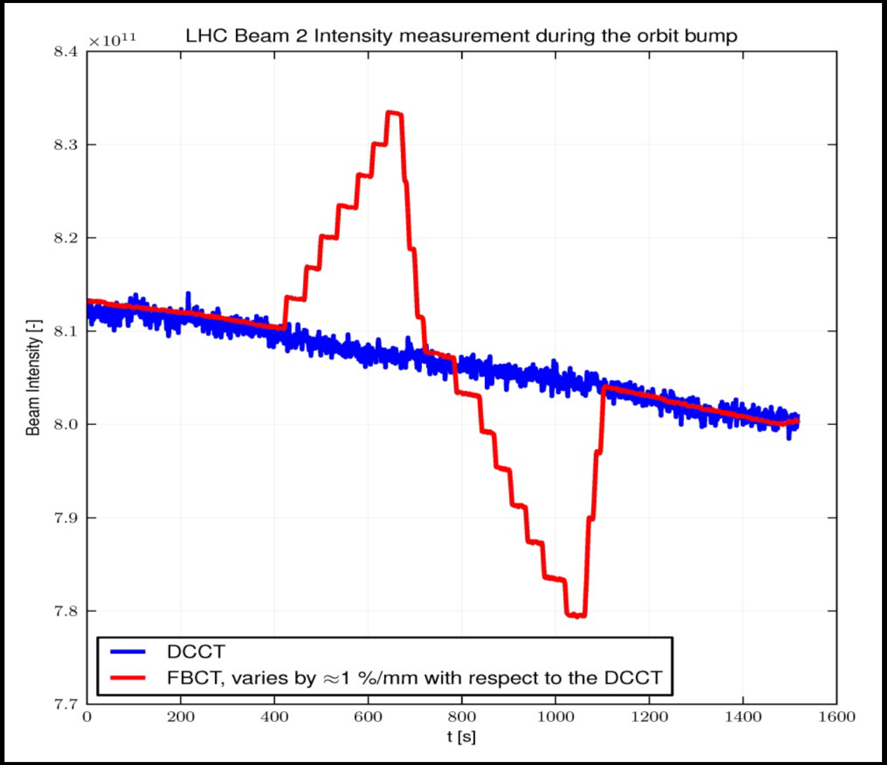




BCT Error Sources & their Mitigation

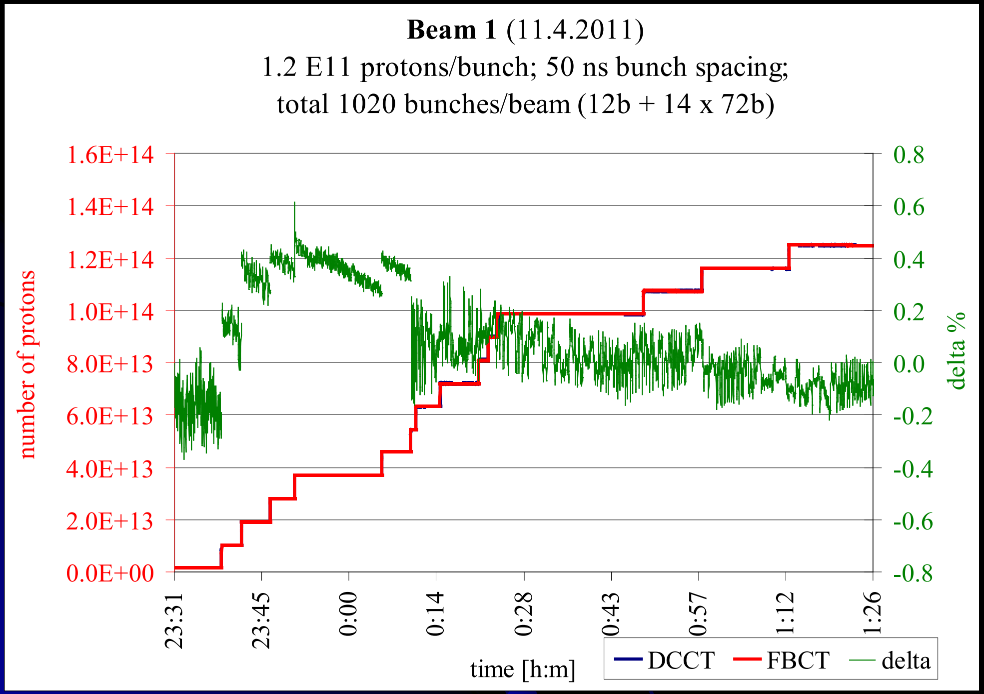
- Bunch length dependence of the fast BCT
  - Mitigated with 70MHz LP filters - still allows bunch-by-bunch measurement
- Bunch position dependence of the fast BCTs
  - At 1% per mm this effect was not at all expected
    - Found to come from commercial toroid used - new monitor under development
  - Fortunately orbit is kept sufficiently stable & limits effect to well below 1%

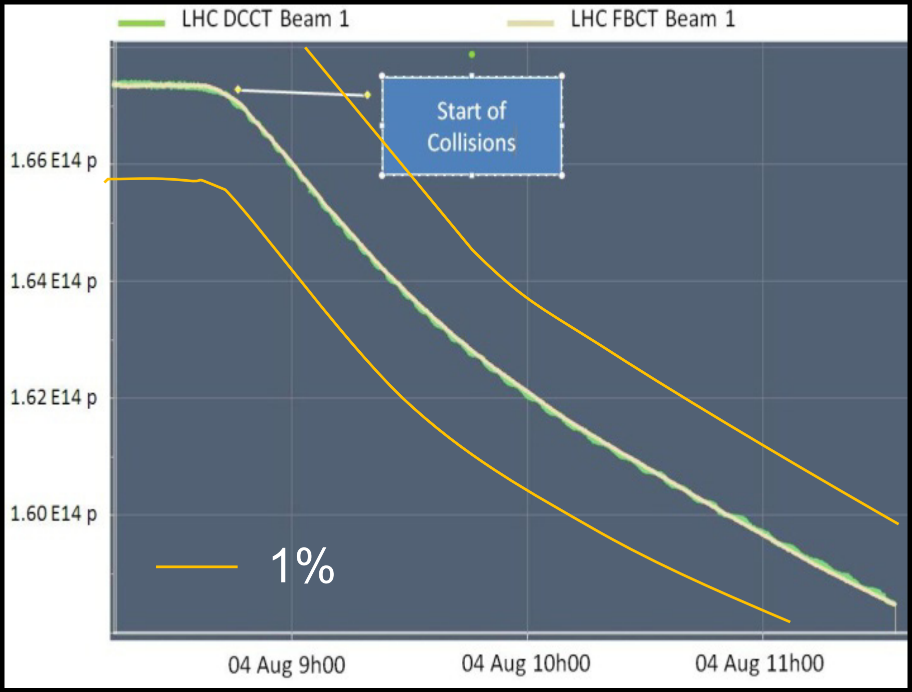




Helping the Experiments - Outlook

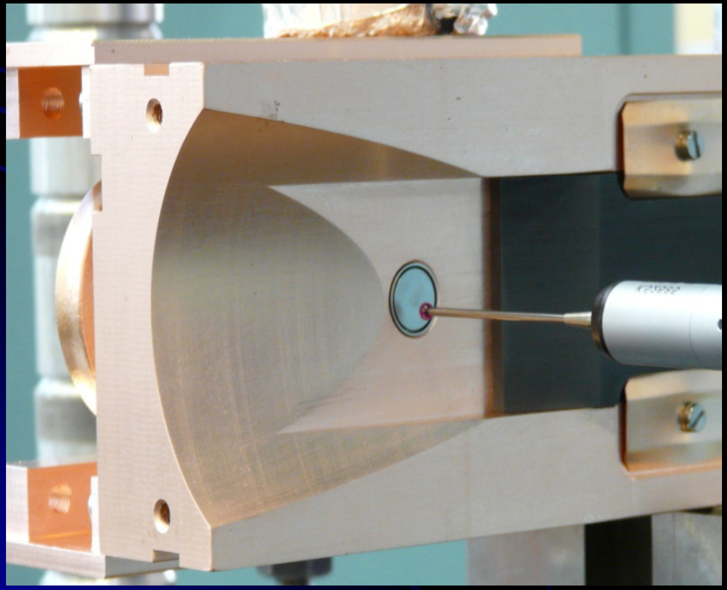
- 2011
  - Important progress made in understanding many error sources
  - Should bring bunch population uncertainties in line with other experimental sources for absolute luminosity determination

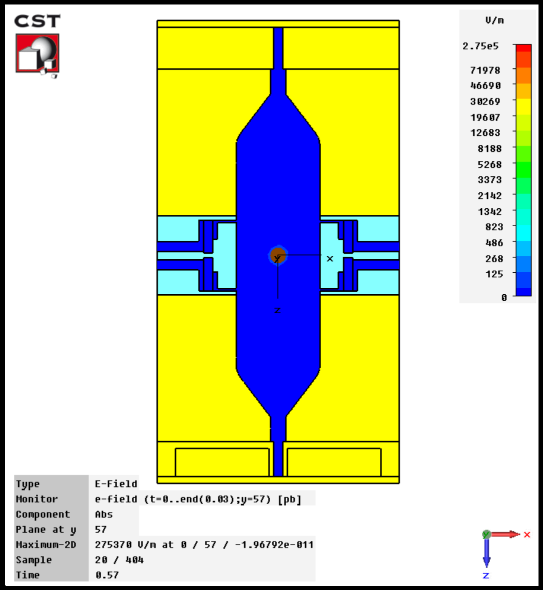




The Future

- Improvements to the LHC Collimators
  - LHC equipped with over 100 collimators
  - Beam-based setup time is non-negligible using current BLM method
  - Tighter tolerances will be required for future LHC operation
- Next generation collimators will contain embedded BPM
  - Should drastically reduce set-up time
  - Will allow constant monitoring of beam v jaw position
    - Design & test of components underway
    - New acquisition electronics being developed
      - Based on compensated diode detection giving sub-micron resolution





Summary

- The LHC is a complex collider with a tremendously high beam power & can only be operated …
  - efficiently with excellent diagnostics
  - safely with a high performance and failsafe beam loss system
- Bunch-by-bunch diagnostics required from most instrument s
  - Proven essential for tracking down instabilities & optimising operation
- Many critical measurements (Q,Q'…) must be performed without significant emittance degradation
  - Possible through sensitive BBQ system & self-excitation of the beam
- Challenges ahead
  - Continued optimisation and understanding of installed instruments
    - Temperature stabilised BPM electronics, new FBCT toroids, tune & damper ...
  - Development of new instruments & techniques
    - Collimator BPMs, fast diamond detector BLMs, fast imaging systems,….